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The Chemistry of Tea

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By

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Preface

Tea is simple: loose-leaf tea, hot pure water, a cup.
I inhale the scent, tiny delicate pieces of the tea floating above the cup.
I drink the tea, the essence of the leaves becoming a part of me.
I am informed by the tea, changed.

—Thích Nhất Hạnh

I start my day by making a quick aqueous extraction of secondary plant metabolites. I stir in a few grams of a purified natural disaccharide, clutch the cup in my hands, inhale a hit of linalool, and take my first swallow of tea. Even if you're not a chemist, you very likely start the day in the same way, making a cup of coffee or tea to enjoy its caffeine-fueled bite and heady aroma, even if you wouldn't describe it in quite those terms. To be honest, even though I'm a chemist, I wouldn't describe it that way either, at least not before the caffeine has kicked in.

This idea for this book grew out of a tweet. "Chemistry question for #ChemTwitter: is there an extractive advantage to the tetrahedral teabag over the traditionally shaped teabag? Or does it just look cooler?" mused @andrechemist. #ChemTwitter had thoughts, but I started to wonder if there was any published research about the effect of a teabag's shape on the taste of the resulting tea. In fact, just what did chemists know about making

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a cup of tea? I was between two terms of teaching and so spent a couple of days rummaging around in the research literature to see what was known about the best way to make tea. Quite a lot, as it turns out, beginning with a mysterious woman chemist from the 19th century to chemists and physicists from all corners of the world in the 21st. And yes, there was research on the best size and shape for a teabag. Just before the start of the COVID-19 pandemic in 2020, I wrote a short essay for the journal *Nature Chemistry* about making the perfect cup of tea from a chemist's perspective, from which this book ultimately emerged.

While that original article was written for chemists, this book is meant for tea-drinkers who may or may not be chemists. If you haven't taken a chemistry course, or haven't taken one recently, don't worry. I've broken down the chemistry you need to know to safely plunge into the molecular world of tea and come out with a better cup. What is a saccharide? Why do I crave the aroma of linalool nearly as much as the buzz from caffeine? And, speaking of caffeine, what does the tea plant get from it? If you are a chemist, I hope you will delight in what follows as much as I did; there is a rich literature out there.

Each chapter begins with a tea pairing. I've given at least two options and tried to include ones that are more likely to be available at a local market, along with more specialty recommendations. Tea is a natural product and one of the joys is that every cup is different, depending on where and when the plant was grown and how it has been treated since. Even the local water used to brew the leaves can change the taste of the final brew, as we will see in Chapter 5.

Want to know more? Each of the chapters ends with a section entitled Going Further. If something in a chapter has piqued your interest, the resources here might be the next step in going deeper into the material. The books that I recommend are generally in print, widely available from booksellers and public libraries, and accessible to the general reader. Journal articles can be more difficult to access because publishers can charge quite a bit for the material. I have tried to select articles that are readable by a non-chemist and available for free. The Reference sections cite material from the primary literature that may be of more interest to those with a science background.

The bottom line is what can chemistry tell us about brewing a better cup of tea, whatever that might mean to each of us. Want to make sure you get every last bit of caffeine you can? Or is the calming floral aroma what you desire? What is the best way to keep a cup of tea hot on the way to work? Sections entitled Brewing a Better Cup have advice on how to get your optimal cup of tea based on the science of that chapter.

I read more than 500 papers while researching this book and drank at least 483 cups of tea (I didn't start counting until I was partway through). I drank deuterated water, spiked my tea with L-theanine, and sampled tea with more than the usual amount of GABA. I wired my teapots and teacups with temperature sensors and measured cooling curves. I tried decaffeinating tea with vodka (not recommended). I did not scrape snow off the plum blossoms in my yard to melt for tea, despite the rave reviews in an 8th century manuscript.

A comprehensive review of the primary research literature on the chemistry of tea would require several volumes, so by no means should this book be considered the final word on all that scientists know about tea, its production, and its infusion. Instead, I have focused here on work that addresses the questions that interested me. I've had a great time steeping in the scientific literature about tea and hope this book will give you the eyes to see what's hidden in your cup of tea too. I invite you to make a cup of tea, perhaps one that is paired with the chapter, and enjoy taking a dive with me into the molecular mash-up that is the world's most popular beverage: tea.

Michelle Francl

Acknowledgments

Thanks must go to #ChemTwitter and, in particular, to @andre-chemist, whose tweet got me started looking at the chemical literature around tea. I'm incredibly grateful to my mother, Lois Cullen Miller, who offered me my first cup of tea on a cold fall morning and who taught me to be curious about the unseen aspects of the world around me, and to my father, Eugene Miller, who always warmed the teapot for me when I visited. My husband, Victor Donnay, was a steadfast support and cheerleader throughout the writing of this book. I have shared many cups of tea and many conversations about chemistry and Star Trek with Lisa Chirlian over the years, which have enriched the writing of this book.

My thanks, too, to Stuart Cantrill, who encouraged me to rummage around in chemistry's odder corners for the Thesis column in *Nature Chemistry*, including my take on the best cup of tea from a chemist's perspective. I first encountered Wilhelmina Green and her paper detailing the chemical analysis of tea infusions while a Herdegen Fellow in 2012 at the Science History Institute in Philadelphia, then the Chemical Heritage Foundation.

Christopher Donnay checked that my combinatorics regarding sucrose were correct and read drafts of the introductory material. Michael Donnay sourced tea for me in the UK and read drafts. Andrew DiDonato read the material on ceramics. Denise Conte, Gene Miller, and Leah Miller read portions of the manuscript.

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Jenna Margolis read and commented on nearly the entirety of the manuscript and I appreciated her perspective on the biological aspects.

Kim Belcher introduced me to Rose Congou tea, which has improved both my afternoons and my writing. Sarah Binau pointed out that caffeine from tea has a different name than caffeine derived from coffee in some languages. I would never have known about the relationship between aluminum and hydrangeas if it were not for a tweet from Christopher Smith, SJ. A conversation with Michelle Mancini and Camilla MacKay at (ironically) a Bryn Mawr College coffee hour led me to explore some of the finer points of teapots.

I must also thank my colleagues, past and present, at Bryn Mawr College for all their support. In particular, I have had the support of the Frank Mallory Professorship in Chemistry, established by Sally Mallory. Trips to Japan with faculty colleagues Marc Schulz and Hank Glassman expanded my experience of tea and its connections to Buddhism. My colleagues at the Vatican Observatory have shared with me the delights of that other caffeinated beverage, at least when you are in Rome. The director of the Observatory, Guy Consolmagno, SJ, pointed me to Masters of Reality and their song *T.U.S.A.*, as well as to some useful methodology for measuring the volumes of odd-shaped objects.

The beautiful photographs that accompany the text were styled and taken by Andrew DiDonato. The idea to include a tea pairing for each chapter was not mine, but that of an anonymous referee of the book proposal. It was a brilliant suggestion, thank you. And, finally, I would like to thank my editor, Helen Armes, for the invitation to spend this time steeping in the chemical literature on tea and for her patience and encouragement throughout the writing of this book.

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CHAPTER 1

A Cup of Chemistry

TEA PAIRING

Enjoy this chapter with a cup of loose-leaf black Assam tea, reminiscent of what Wilhemenia Green used for her analysis of tea, or a Twinings Irish Breakfast Tea.

1.1 THE MYSTERIOUS WILHELMINA GREEN

In the spring of 2012, I got on a train four days a week to meet up with chemists from the 19th century, or at least their ghostly imprints pressed into the pages of scientific journals. One of those chemists was Wilhelmina Green, whose 1885 paper, "On the infusion of tea," I first encountered while browsing *The Chemical News* in the Othmer Library in Philadelphia. In it she carefully and clearly laid out her chemical analysis of an infusion of black tea. Assam Pekoe-Souchong, brewed in a white porcelain pot, to be as precise as Green herself was. I was as taken with Green's attention to these small details as I was by encountering a woman chemist in this era, publishing on her own and not tucked into her husband's paper. Green, in turn, was surprised at how little chemists knew about the chemical composition of brewed tea, a gap in the literature she briskly

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set out to remedy. She deftly explored the chemistry of the brew with an eye to figuring out the best way to extract the desirable compounds.

After water, tea is the most popular beverage in the world. It is estimated that more than two billion cups a day are drunk and five million tons of dried leaves are harvested each year. Apparently, you cannot write about the chemistry of tea without making note of its popularity. The authors of virtually every journal article I read while researching this book—more than 500 of them—assert this fact in their introduction. I occasionally wonder if tea-drinkers have a bit of an inferiority complex relative to coffee-drinkers, which is why researchers are so insistent on reminding the readers that tea is important to more people than coffee. Or does the L-theanine in tea make us less voluble than our coffee counterparts?

Tea has piqued scientists' curiosity not just because of its popularity, but because of the health benefits that for centuries have been attributed to the drinking of tea. Tea invigorates, tea calms. It has high levels of valuable antioxidants, it is neuroprotective. Tea has potential risks too. Is the caffeine it contains addictive? Does it contribute to the development of kidney stones, or gout, or liver failure? Does drinking hot tea increase the risk of cancer? Is green tea healthier than black tea?

The chemistry of tea is also entwined with more fundamental discoveries in science. In 1902, Emil Fischer was awarded the second-ever Nobel Prize in Chemistry, in part for his work on caffeine. In 1913, Hungarian chemist George de Hevesy had tea with another young scientist working at Manchester, Henry Moseley. de Hevesy wondered aloud if there was a way to follow the water molecules in the tea through his body. Moseley, a brilliant young physicist who that same year would uncover the key to the ordering of the elements in the periodic table, thought it unlikely. But 20 years later, with the help of Harold Urey's gift of heavy water and a few dozen goldfish, not to mention liters of distilled urine, de Hevesy would crack the problem. The work would contribute to de Hevesy's 1943 Nobel Prize in Chemistry for the development of isotopic tracing—a phenomenon that has spawned such innovations as

PET scans and methods for mapping ocean currents. In 1925, Ronald Fisher's exposition of the null hypothesis, a fundamental notion in statistics and data science, emerged from a conversation (over tea) about how to test the claim that someone could tell the difference between a cup of tea to which milk had been added and a cup where the milk had been put in first.

Like Wilhelmina Green, I want to know what is in my cup of tea and how to use what is known about the chemistry of tea to make the best cup. I'm curious, too, about what happens in my body, not just to the water in that teacup, but to the rich mix of chemicals it contains when I drink it. This book takes a dive into a cup of tea to see it as a chemist might—and yes, addresses the critical question of whether milk or tea goes in the cup first.

1.2 WHAT THIS BOOK IS ABOUT

Chemistry and tea, of course. Which means, as a starting point, I have packaged up in this chapter a very short course in chemistry for those who may not have a background in this field. Make a calming cup of tea and join me to discover four of the basic concepts that underlie much of modern chemistry and learn how to decipher the structures and names of molecules. If even that feels like too much, there is a three-paragraph summary below (**Chemistry TL;DR**) that should get you started, although at points in the book you may want to backtrack and get a little more in-depth information.

Those who remember some of their secondary school or university chemistry (and chemists, biochemists, biologists, and the like) should jump right in at the second chapter, **Reading the Tea Leaves**, which tackles the chemistry that underlies the processing of tea leaves. How do the leaves of a single plant give rise to so many different styles of dried tea ready to be brewed? What do bruised apples, molds, and fungi have to do with the production of tea?

Arguably the molecular star of tea is caffeine, the world's most widely used psychoactive substance. **The Drug in the Cup** explores what caffeine does in the brain, how caffeine ends up in the tea leaf, and how to get it out if you would prefer to have a little less zing in your cup. There are, as it turns out, thousands of other molecules in a cup of tea besides caffeine—along with some surprising minerals, including fluoride and aluminum. **The Taste of Zen** takes a tour of this rich molecular soup and examines the role some of these compounds play in creating the taste and aroma of tea infusions.

The conditions under which the chemical compounds in tea leaves are extracted affect the final infusion, as anyone who has suffered a cup of tea made with lukewarm water can attest. **The Agony of the Leaves** considers the ways in which the water temperature and the time permitted for the infusion can change the amount of caffeine and antioxidants in a cup. It also unravels the mystery of the white film that sometimes appears on tea that has been prepared using a microwave oven (and how that might be related to the ring left in your bathtub).

Milk first or tea first? People have strong feelings about this, but are there chemical reasons for choosing one way over the other? **Sugar and Spice** takes a molecular tour of the things we add to tea, from milk and sweeteners to the spices that warm a cup of chai. Why might you consider adding a pinch of salt to tea?

Does the shape of a teabag matter? What about the shape of a teapot? **Earth, Water, Fire, and Air** explores these questions, as well as how to make synthetic rocks—ceramics—to contain tea. How water gets hot and the best strategies for keeping tea that way, from tea cozies to thermos flasks, finishes our chemical tour of tea.

1.3 WHAT THIS BOOK IS NOT ABOUT

When someone offers us a cup of tea, we assume we are getting a beverage that is made by immersing the leaves or other parts of some plant in hot water for several minutes. The leaves are then removed and we might be offered a sweetener, some lemon, or a dairy product to stir into our cup. Chemists call this an infusion, while an herbalist might call it a tisane.

Tea in this book refers to an infusion made from the leaves of one particular evergreen shrub, native to Asia and now grown worldwide: *Camellia sinensis*. The name for tea's Linnaean genus, *Camellia*, honors Georg Kamel,† a 17th century Jesuit brother and botanist who worked in the Philippines. *Sinensis* is Latin for "from China." There are two principal varieties of tea, *Camellia sinensis* var. *assamica* and *Camellia sinensis* var. *sinensis*. While "herbal teas," such as infusions of mint, rooibos, and chamomile, have their own unique and fascinating chemistry, I won't discuss them here.

This book is also not about the history of tea, nor the sociopolitical ramifications of that history. The history of tea is many millennia long, complex, and—at certain times and in certain places—tightly interwoven into Western colonialism. The brief history I give later in this chapter is superficial in the extreme and not in any way comprehensive. It is not my intention to cover this complicated and often fraught story here because to do it justice would require its own book. Readers who want a historical context for tea may consult the **Further Reading** at the end of the chapter for suggestions of excellent histories of tea from a variety of perspectives.

1.4 AN INCREDIBLY BRIEF HISTORY OF TEA

The chemistry behind a cup of tea is ancient chemistry, older perhaps than the chemistry of ceramics, or of dyes and paints, or of brewing. Archeological evidence for the medicinal use of plants by modern humans goes back at least 60 000 years, 40 000 years earlier than known human forays into the making of pottery. So, what made people think of soaking leaves in water (hot and otherwise) and drinking the resulting infusion in the first place? The short answer might be zoopharmacognosy: animals do it. Animals, including chimpanzees and porcupines,‡ have been observed to engage in zoopharmacognosy, deliberately chewing specific plants and either swallowing them or applying them externally to treat illnesses and injuries. In other words, extracting pharmacologically active material from plants is a behavior we have both inherited from our primate progenitors

†Kamel did not describe camellias, nor the tea plant, in any of his work, although he did publish on *Strychnos ignatii*, the strychnine-containing "beans of St Ignatius". Coincidentally, Kamel was from the town in Moravia where Gregor Mendel would later do his groundbreaking work on heredity in plants.

‡In Tanzania, Babu Kalunde discovered the ability of an extract of the mulengelele plant to treat a gastrointestinal infection by observing sick porcupines eating it.

and observed in the natural world. (One of the origin stories for coffee, in fact, has a goatherd observing that when his goats ate the berries from a particular tree, they did not sleep at night.)

The origins of both the *C. sinensis* plant and the practice of making tea from its leaves are lost in the mists of time. Wild *C. sinensis* plants have never been identified. Evolutionary biologists see genetic evidence that implies tea plants were domesticated not in a single place, but perhaps in as many as three different places. *C. sinensis* plants found outside tea gardens are thought to be feral—descended from plants that had previously escaped the confines of cultivation—rather than wild. We are left with myths and indirect evidence as to the origin and history of the cultivation of *C. sinensis*. One legend attributes the origin of the tea plant to the sixth century Buddhist monk, Bodhidharma, who is credited with the founding of Zen Buddhism. He is said to have fallen asleep while meditating in a cave. Angry with himself, he tore off his eyelids and threw them out of the cave, where they took root and grew into a plant whose leaves, when infused, would make a stimulating beverage, keeping sleepy monks from nodding off during their meditations.

Archeologists suggest that the cultivation of *C. sinensis* and the practice of drinking of tea made from its leaves goes back at least 600 years before Bodhidharma. Evidence from burial sites in Xi'an, a city in the central Chinese province of Shaanxi and the easternmost outpost of the legendary Silk Road, suggests that tea was being drunk and traded as early as 2100 years ago. Even early on, tea was an exotic commodity, grown and produced in places most people could not imagine and would never visit. In the middle of the eighth century, tea master Lu Yu wrote *The Classic of Tea*, describing the cultivation, production, and brewing of tea using methods that the modern tea-drinker would recognize. The drinking of tea remained tightly linked with Buddhism. Tea was introduced to Japan along with Zen Buddhism by the Buddhist monk Eisai. By the 16th century, a culture of tea thrived in Japan, complete with elaborate ceremonies and dedicated spaces devoted to the Way of Tea.

Tea spread westward (and eventually space-ward). North African scholars and explorers of the 14th century, Ibn Battuta and his contemporary Sa'id of Mogadishu, wrote about the customs surrounding tea they encountered in China. Tea came to the attention of Europe much later; the earliest references to tea are not until the 16th century. Giovanni Botero, in his book *On the Causes of the Magnificence and Greatness of Cities*, describes tea as an herb from which the Chinese pressed "a delicate juice." He emphasizes the health benefits of tea over alcohol, an argument that coffee-drinkers would also wield to good effect in this same period. The wholesale importation of tea into Europe began with the Dutch at the beginning of the 17th century. Shortly thereafter, tea became popular in England and from there immigrated to the nascent United States of America. The English, who had been indirectly trading opium for Chinese tea, brought Chinese tea plants to what is now modern day India and established tea gardens there, although tea was long known and already cultivated on the Indian subcontinent. Early in the 20th century, tea emerged as a crop in subtropical Africa. Tea has even had a part to play in trouble-shooting equipment on the International Space Station.

1.5 CHEMISTRY LESSONS

This book is about the chemistry of tea. While chemistry is my job, five days a week, it may have been a long time since you took a chemistry class, or you may never have taken one at all. Certainly chemistry is a rich field that you can spend years studying, but with a little background you can have a deeper appreciation of the world at a molecular level. You can learn to see into not only a cup of tea, but everything you encounter, with the eyes of a chemist.

In order to immerse ourselves in the chemistry of tea, we will need two things. The first is an overview of the four big ideas chemists use to explain how atoms and molecules behave. The second is the equivalent of a magic decoder ring, a brief lesson in how to decipher the weird and tongue-twisting names chemists give to molecules and the cryptic structural drawings we use.

To be fair, you may not want to wade through all the chemistry I have on offer before you plunge into the chemistry of tea specifically. If even a very short introduction to chemistry is not your cup of tea, the bare essentials are in the three paragraphs that immediately follow. You can always return to this chapter for more details if you are curious as you read further.

1.6 CHEMISTRY TL;DR[§]

Matter, including everything in my cup of tea, is made up of atoms. Electrons are the glue that holds atoms together. The behavior of materials depends on the arrangement of the atoms, not their source, whether natural or synthetic, or their names.[¶] Atoms can be rearranged to make new materials. Most of the molecules I discuss in this book are built on a carbon atom framework decorated with hydrogen atoms, oxygen atoms, and nitrogen atoms. This is what chemists mean by an organic molecule.

Molecules can react with each other when they get close. Many reactions can be understood as interactions between positive and negative charges; in the chemical world, opposites really do attract. Molecules can also hand electrons off from one to another, a process called oxidation.

Chemists show the framework of carbon atoms in organic molecules by drawing lines. So, a hexagon is really six carbon atoms arranged in a circuit (Figure 1.1). Atoms connected by two or three lines are more tightly attached to each other than those with one line. Hydrogen atoms are generally not shown. Long tongue-twisty names are often compact instructions for assembling the molecule. Most chemical names contain (for chemists at least) clues to the structure, and therefore clues to the function, of the molecule. With no apologies to Shakespeare, [(2*R*,3*R*,4*S*,5*S*,6*R*)-2-{[(2*S*,3*S*,4*S*,5*R*)-3,4-dihydroxy-2,5-bis(hydroxymethyl)oxolan-2-yl]oxy}-6-(hydroxymethyl)oxane-3,4,5-triol by its other name—sucrose—tastes just as sweet.

Now feel free to skip ahead to the next chapter on the chemistry of caffeine, or push on to learn more about the chemistry lurking in your cup of tea.

1.7 A SLIGHTLY LONGER COURSE IN CHEMISTRY

I have taught introductory chemistry for four decades, a course that consists of more than a hundred hours of lecture over a year's time. Don't tell my students, but you don't need that many hours

§TL;DR = too long; didn't read.

¶It may seem obvious that what a molecule is called has nothing to do with how it works, or how safe it is, but people are often advised not consume anything that an eight-year-old cannot pronounce, or that your grandmother would not recognize. It's not helpful advice and unnecessarily disparages grandmothers.

(a)

(b)

(c)

(d)

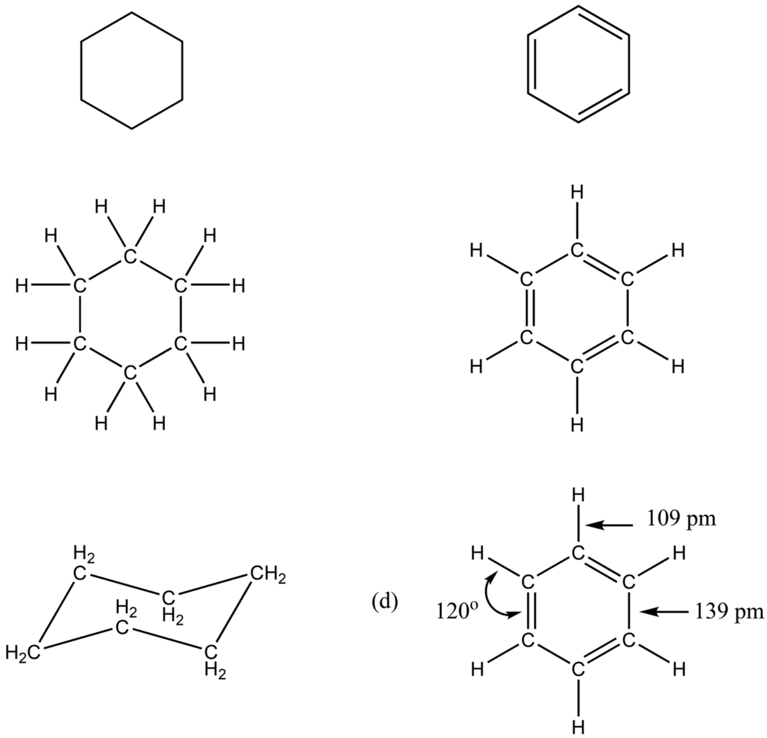


Figure 1.1 (a) Cyclohexane (C_6H_{12}) and benzene (C_6H_6) represented as standard chemical line structures. (b) Cyclohexane and benzene with all their carbon and hydrogen atoms shown explicitly. (c) Cyclohexane shown as its puckered chair shape. (d) The bond distances and angles of benzene.

of instruction to qualitatively understand much of the chemistry that you encounter in daily life.[I] Here, as I do with my students, we'll look at some of the major themes that drive chemistry and learn a bit about the primary language of the chemical world: molecular structure.

To start, what exactly is chemistry, at least relative to other sciences such as biology or physics? There's an old joke that says if it is green or wriggles, it is biology, and if it explodes or smells, it is chemistry. More seriously, chemistry might be simply defined as the science of change, working to understand why and how

[I]You do need that time in seat if you want to be able to deal with chemistry quantitatively. I'm leaving out all the equations.

one material transforms into another. Why does tea get darker in color after it sits for a time? Why does a white haze appear if you use a microwave to heat the water for your tea?

Chemistry is also the science of molecular behavior. There is some truth in that old joke, as many chemical processes release compounds that smell. Despite the joke's subtext that smells are an unfortunate thing, when it comes to tea, scent is a desirable thing. Chemistry can help answer the question as to why some of these molecules smell the way they do, as well as many other properties. What gives Earl Grey tea its distinctive aroma? Why is green tea tinged a pale ochre and black tea deeply copper-toned? Why does caffeine give us a rush of energy?

There are not hard and fast lines between the different areas of science. Much interesting work happens at the intersection of fields. For example, biochemistry, which sits at the crossroads of biology and chemistry, tackles the molecules of life. Even though the main focus of this book is the chemistry of tea, we will often wander from chemistry into biochemistry, and even make brief forays into biology, physics, and engineering.

1.8 CHEMISTRY'S BIG IDEAS

There are a few big ideas chemists wield to understand how the world works at the molecular level. We can use four of them to understand almost all of the chemistry I will discuss in this book.

The first notion is that atoms are the building blocks of matter. You can think of them like Lego blocks. You can use the same blocks to make a house, or a car, or a spaceship. They can be combined in many different ways, but not every block can be connected to every other block, and only certain orientations between blocks will work. The shapes of the blocks constrain what you can make from them. Chemistry is the science—and the art—of knowing how to combine atomic building blocks to make different materials, given the constraints nature imposes on the connections.

All matter is made up of atoms. (There is another bad joke that says you can't trust atoms because they make up everything.) In this sense, chemistry is fundamental to understanding how the tangible universe works. A molecule is a discrete collection of atoms with a fixed structure. A formal definition of a molecule is that it is the smallest unit into which a chemical compound can be broken down and still retain its fundamental identity. Molecules are often what we think about when we think about a chemical. But matter can also take other forms as well—for example, many crystalline substances, such as table salt, are not made up of individual molecules, but of repeating patterns of charged particles called ions. Polymers, such as the common plastic polyethylene, are long chains of atoms. Diamond is a network of carbon atoms extending for long distances in all three dimensions. Molecules can be small, like water, which is made up of only three atoms. They can also be enormous; proteins are molecules that may have 10 000 or more atoms.

Atoms are built from electrons, tiny negatively charged particles, and nuclei, which are clusters of positively charged particles called protons and uncharged particles called neutrons. The identity of an atom is determined by the number of protons in its nucleus. All atoms that have one proton in their nucleus are hydrogen atoms and all atoms with six protons in their nucleus are carbon atoms, regardless of the number of neutrons they contain. The familiar periodic table lists the number of protons along with the standard chemical symbols used to represent atoms. Chemists and biologists can use subtle changes in the nucleus of an element, such as the addition of an extra neutron, as an atomic level tracking device. This is how George de Hevesy was eventually able to track the water from a cup of tea through the human body.[**]

One way that atoms connect to each other is through sharing their electrons. The two hydrogen atoms in water, H_2O, are each linked to the central oxygen atom by a shared pair of electrons, what chemists call a covalent bond. Sharing more than one pair leads to a shorter and stronger bond: two pairs make a double bond, three pairs a triple.

The second big idea is that opposites charges attract each other, while like charges repel each other. This is another way that atoms connect to each other. For example, in table salt, the positively charged sodium ions (Na^+) are attracted to the negatively charged chloride ions (Cl^-). Chemists call these electrostatic

[**]He also distilled many liters of his (or his laboratory assistant's, the paper is a bit vague) urine.

attachments ionic bonds and the resulting materials are often crystalline in nature. Water molecules have a positively charged side and a negatively charged side and so can insinuate themselves between charged ions, making many of these compounds soluble in water. The larger the charges, the more tightly held the ions are to one another and the less likely they are to be soluble in water. So, while table salt, comprised of +1 and −1 ions, readily dissolves in water, calcium carbonate, made up of Ca^{2+} and CO_3^{2-} ions, does not. Instead, it makes seashells and the scum that sometimes floats on your tea.

As anyone who has done any cooking knows, you have to stir things to get them to combine. Chemistry is just a specialized form of cooking (or *vice versa*) and the same principle applies. The third big idea that chemists wield is that molecules and other materials must get into close proximity to each other in order to react. This is often most easily done when things are in a liquid form, where the molecules and atoms are close together and easily able to move around. This lets them approach each other at the correct orientation. Molecules are very mobile in the gas phase, but compared with a liquid they are much further apart. Water molecules in the gas phase, as in the steam swirling above your cup of tea, are about 1500 times as far apart as they are in the liquid in the cup. Conversely, while molecules in the solid phase are about as close together as those in a liquid, they are trapped in a single spot like patrons in a movie theater and can only make contact with their nearest neighbors.

The last fundamental idea—and the most important one—we will find helpful in understanding the chemistry of tea is that the molecular shape controls molecular function and molecular properties. It is such an important idea that I tell the students in my introductory chemistry course that if this is the only thing they remember from my class in years to come, I would consider my work a success. Neither the name of the molecule, nor its origins—natural or synthetic—has any influence on its behavior.

Shakespeare said a rose by any other name smells as sweet. The same is true of molecules. You sometimes hear that you shouldn't eat anything an eight-year old can't pronounce. For example, while 4-hydroxy-3-methoxybenzaldehyde sounds off-putting, perhaps even dangerous, it is just the formal name of the main chemical compound in vanilla extract. By either name it smells wonderful and you would not hesitate to use it in a recipe. We will see later in this chapter why chemists use such awkward names and how to decode them.

Just as the name we give a molecule has no effect on its behavior, neither does its source. Western chemists have known for almost 200 years that you can make compounds indistinguishable from those found in living organisms using inorganic materials—that is, starting from things found in rocks and minerals. The 19th century German chemist Friedrich Wöhler showed that you can make urea molecules from potassium cyanide and ammonium chloride that are identical to the urea molecules extracted from urine. Two decades later, Hermann Kolbe showed it is possible to make acetic acid, the main ingredient of vinegar, from non-biological materials, in this case carbon disulfide.

Some people mistakenly believe that compounds made by biological organisms have special qualities. For example, beta-carotene, the pigment that gives carrots their characteristic orange color and is also found in tea, is sometimes used to color food products as a substitute for what are called "coal tar dyes." At the atomic level, a beta-carotene molecule made by a carrot or a tea plant is completely identical in structure to a beta-carotene molecule synthesized by a chemist in the laboratory. Once you get down to this level, there are no remnants of the carrot clinging to the naturally produced beta-carotene, nor traces of the laboratory bench stuck to the synthetic version. Since their structures are the same, we can expect them to have the same properties and for them to behave identically. In fact, most of the beta-carotene that is used to color food is made synthetically in chemical factories, not extracted from carrots. And you can make those "coal tar dyes" from plants! It is the structure, not the source or the name, that matters when it comes to molecules.

Still, it can be very hard to get past the notion that the source of a molecule matters. Psychologists have shown that just the thought of disgust can be a powerful motivator for human behavior. For example, would you stir your soup with a fly swatter that had been previously used to swat flies, but subsequently had been cleaned and sterilized? I wouldn't, even though I understand there are no remnants of the fly remaining, nor any other contaminants on the swatter. In the same way, it can seem reasonable to assume that because beta-carotene can be extracted from something edible—carrots—it is somehow more natural, and perhaps safer to eat, than the dyes made from sticky and inedible coal tar. But atoms truly have no memories of where they came from. Just as the same Lego block can be used to build a cottage or a starship, the carbon and other atoms that make up carrots are no different from the atoms found in coal tar.

Most of the molecules I'll discuss in this book are so-called organic molecules. These are molecules that are built on a carbon and hydrogen framework. In addition to carbon and hydrogen, these molecules may also contain oxygen, nitrogen, sulfur, fluorine, or chlorine. Chemists classify molecules that don't contain carbon as inorganic. Most herbicides and pesticides are organic molecules, in the chemical sense of being based on a carbon frame. Organic has a quite different meaning in chemistry than it has when it referring to fruits and vegetables!

1.9 HOW TO READ A CHEMICAL STRUCTURE—OR WHAT DO MOLECULES REALLY LOOK LIKE ANYWAY?

In 2008 Joon Mo Kong created a molecular structure to illustrate the New York Times review of Mary Roach's book *Bonk* about the science of sex. Chemists flipped out. They weren't bothered by the frank discussion that opens the review, but the illustration that accompanied the article offended them to the core. They wrote letters to the editor pointing out its implausibility—"It's complete nonsense, you can't have five bonds to carbon!"—and asking for the structure to be corrected. But there was no correction needed. Kong had simply used the familiar elements of chemical line structures to spell out the word "SEX." It was glaringly obvious to anyone who was not trained as a chemist—and utterly invisible to anyone who was (see Figure 1.2).

Because one of the major ideas in chemistry is that molecular structure dictates molecular function, chemical structures are an important part of how chemists think about and communicate what is happening on a molecular level. We have developed a number of different shorthand methods that allow us to quickly outline the important parts of a molecule, as well as some more sophisticated methods for visualizing more subtle effects. What follows is a short course on how to see these different representations of molecules as chemists see them.

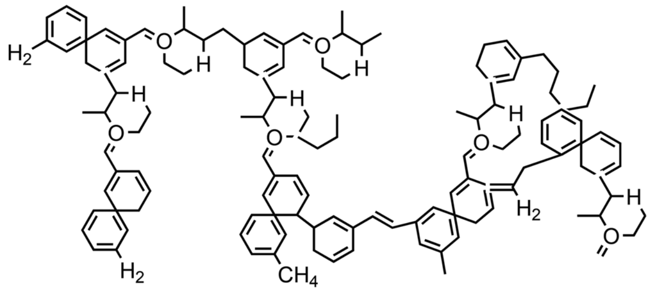


Figure 1.2 The word "TEA" written using elements from chemical line structures in a way that would make any chemist wince.

Chemists are indoctrinated from the earliest days of their training to see the atoms behind the spare and elegant line structures like those Joon Mo Kong riffed off to create his illustration. We rely on the underlying rules that atoms must follow in a molecule to read these figures. The International Union of Pure and Applied Chemistry, known as IUPAC, maintains standards for many things in chemistry. Their recommendations on drawing chemical structures take up 133 pages! Here's a much shorter introduction to these structures and their meaning.

Go back to Figure 1.1(a) and compare the two hexagons. At a single glance, chemists see these to be two entirely different molecules: C_6H_6 (benzene) and C_6H_{12} (cyclohexane).[††] Because they have (to a chemist) such different structures, chemists expect them to have different properties. Benzene, for example, is a known carcinogen, with an almost perfume-like odor. Cyclohexane, by contrast, smells like cleaning fluid and is not thought to cause cancer in humans.

While at first glance there doesn't appear to be any carbon (C) or hydrogen (H) in these molecules, chemists are trained to see each vertex as a carbon atom. Bonds between carbon and hydrogen aren't usually shown, partly because they clutter up the picture and partly because they are often less reactive than other bonds. So, while we could draw these molecules as in Figure 1.1(b) with all their carbon and hydrogen atoms explicitly shown, chemists generally don't. Since chemists know that

[††]Fun fact for chemists: this wasn't always true. Up until the middle of the 20th century, many chemists represented benzene as a simple hexagon, indistinguishable from cyclohexane.

each carbon atom must have four covalent bonds to it—that is, four possible sites for attachment—we can always mentally add in the hydrogen atoms. Covalent bonds, connections between atoms made by sharing electron pairs, are depicted by lines. One line is a single bond, two lines means the atoms are linked by a double bond, and three indicates a triple bond. The more bonds between atoms, the stronger the attachment and the harder they are to break apart.[‡‡]

There is still more that chemists can read into these structures. Chemists know that the atoms attached to a carbon with a double bond point at the corners of a triangle, while the atoms attached to a carbon with four atoms point at the vertices of a tetrahedron (Figure 1.3). We often use wedges and dashes to indicate that bonds are popping out of the page or fading behind it.

As a result, chemists can intuit from these diagrams that benzene is flat like a plate, while cyclohexane is puckered like a recliner chair (Figure 1.1(c)). Dame Kathleen Lonsdale, an Irish chemist and crystallographer, definitively determined in 1929 that benzene is planar—until then, many organic chemists believed it was chair-shaped. Lonsdale worked up the data from her experiments at home while the parent of a newborn daughter. I imagine many cups of tea were consumed in the process.

Chemists also have a rough sense of the distance between atoms. Single bonds between carbons are about 150 pm long, whereas those between a carbon and a hydrogen are a bit more than 100 pm (Figure 1.1(d)). A "pm" is a picometer, which is

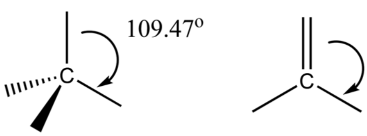


Figure 1.3 Left: a tetrahedral carbon atom with four points of attachment, all set at angles of 109.47° to each other. The solid wedge is read as popping out of the page; the dashed wedge as receding behind the page. Right: a trigonal planar carbon atom. It has three points of attachment, all 120° apart. The double line indicates that one point of attachment is a double bond. Both of these carbon atoms can make a total of four bonds.

[‡‡]What exactly is a chemical bond? The short answer is "an electron pair"; the long answer is "quantum mechanics".

one-billionth of a meter, or about one ten-thousandth the thickness of a page of this book. In other words, molecules are outrageously small and atoms are unbelievably tiny. There are billions more atoms in a teaspoon of water than there are stars in the Milky Way and far more molecules in your body than solar systems in the entire universe.

Small as molecules are, they have more heft than the line structures would suggest. Sometimes chemists use ball and stick models to get a better sense of the space that the atoms in the molecule occupy. The atoms are represented as spheres and the bonds between them as sticks (Figure 1.4). The atoms are usually color-coded, typically black for carbon, red for oxygen, blue for nitrogen, and white for hydrogen, although if you were able to see the atoms, they would all be the same color.

If you were able to take a picture of an atom, you would see that the nucleus is extraordinarily tiny compared even to the size of the overall molecule. The diameter of the nucleus of a carbon atom is about 5 fm. An "fm" is a femtometer, which is one-quadrillionth

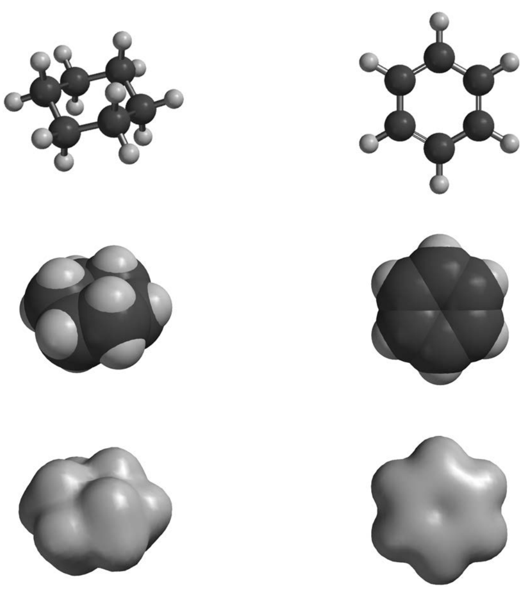


Figure 1.4 Upper panel: ball-and-stick representations of cyclohexane and benzene. Middle panel: space-filling representations of cyclohexane and benzene. Lower panel: electron density surfaces from a quantum mechanical calculation.

of a meter—that is, one 1 000 000 000 000 000th of a meter. The diameter of a carbon nucleus is about one-millionth the diameter of a human blood cell, too small to see using a regular light microscope or with any imaging technique currently known. Even chemists find it difficult to imagine how small the nucleus of an atom is. The diameter of a carbon nucleus is about one 10 000th of the overall length of a benzene molecule.

The ball and stick models still aren't as representative of reality as they could be. We can now make images of molecules using techniques such as X-ray diffraction (the technique used to discover that DNA has a double helix structure) and atomic force microscopy (a high-tech method to "feel" the texture of a surface at the atomic and molecular levels). Seen this way, molecules look like a bunch of fuzzy tennis balls smashed together. When we look at these images, what we are seeing are not the tiny nuclei, but the electron cloud that surrounds them. Chemists call the models that look most like these clouds of electron density "space-filling models" because they show us most clearly the space that a molecule occupies (Figure 1.4). We generally color code the atoms to remind us which nuclei are which, but the images show us that all the atoms look identical.

Though all these representations of molecules imply that they are rigid and motionless, molecules are always on the move. Molecules in the gas and liquid phases never sit still, but continuously dash about their containers, bumping into each other and the container's walls. At 100 °C the gaseous water molecules that are streaming out of a boiling tea kettle are moving on average at nearly 700 m s^{-1} (2500 km h^{-1} or 1500 mph), almost twice the speed of sound. As they move about in either the liquid or gas phase, the molecules are also simultaneously wiggling and tumbling. Bonds stretch and bend, behaving more like springs than lines or sticks. Even in the solid phase, where molecules are essentially pinned in a single position, they are still quivering and tumbling in place.

1.10 DECODING CHEMICAL NAMES

The same chemical structure can be called by many different names. There are trivial (or common) names, trade names, and systematic names, the latter being the formal name for a molecule. For example, H_2O is commonly called water, even by chemists. Even though you will hear people call water "dihydrogen monoxide" in an attempt to sound ultra-scientific, the formal IUPAC-approved systematic name is actually oxidane. Vinegar is primarily acetic acid; the IUPAC systematic name for acetic acid is ethanoic acid. Teflon is a trade name for a polymer of tetrafluoroethylene, which is used as a nonstick coating on cooking pans. Its systematic name is poly(1,1,2,2-tetrafluoroethylene).

Chemists build the names of molecules like they build molecules: from smaller pieces. And while these names can seem like alien tongue-twisters, there can be a natural beauty hidden inside both trivial names and the building blocks used for systematic names. The systematic stem in ethanol, CH_3CH_2OH, the kind of alcohol that we drink, is eth- and indicates the presence of a two-carbon atom chain in the molecule. It is derived from the word ether, the material thought to fill the sky, the stuff of heaven. Which a beer after a long day of work might be. A butyl chain has four carbon atoms in it and gets its name from a down-to-earth food—butter—because butyric acid, which smells of rancid butter, was found to have four carbon atoms in it.

Scratch the surface of a molecule's trivial name and you may find a clue to where it is found in the natural world, or even a dash of whimsy, as the structures in Figure 1.5 suggest. Thearubigin, the chemical responsible for the red–brown color of tea, gets its trivial name from the botanical family in which the tea plant is found, Theaceae, and its ruby color. Shikimic acid, found in some teas, gets its name from the flower of the star anise plant: shikimi in Japanese. If you squint, penguinone bears a passing resemblance to a penguin and snoutane looks like the snout of a crocodile.

Chemists use the complex names of molecules as a compact way to encode their three-dimensional structures. The full formal name of a molecule tells an advertent chemist precisely what the molecular structure is. These names are cumbersome even for chemists to use because they are often long and can contain a jumble of numbers and Greek letters. So, chemists use common names, essentially short nicknames, for their molecules. It is much like the way a GPS system uses latitude and longitude to precisely locate a place on a map. Generally, this is not how you would tell a friend how to find your house—instead, you would

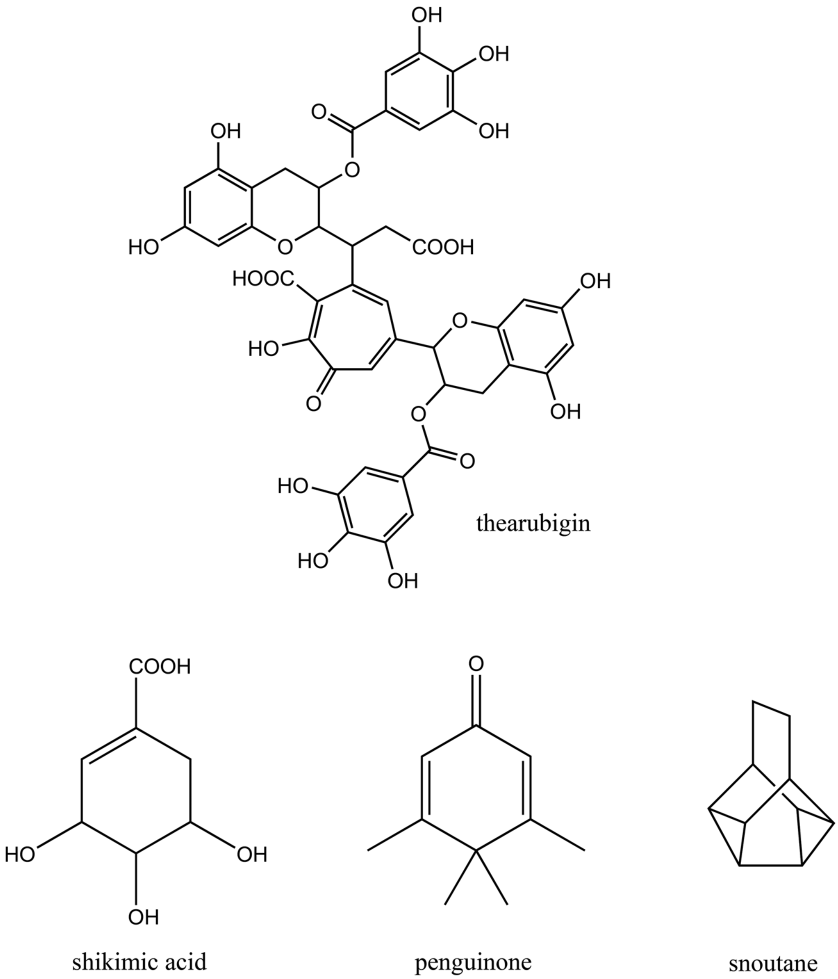


Figure 1.5 Standard chemical line structures for thearubigin, shikimic acid, penguinone, and snoutane.

probably use your address or a local landmark. So, rather than say I had an aqueous solution of (2*R*,3*R*,4*S*,5*S*,6*R*)-2-{[(2*S*,3*S*,4*S*,5*R*)-3,4-dihydroxy-2,5-bis(hydroxymethyl)oxolan-2-yl]oxy}-6-(hydroxymethyl)oxane-3,4,5-triol (whew!), I am far more likely to say I have a solution of sucrose—ordinary table sugar—in water.

Given a molecule's systematic name, a chemist can reconstruct its shape and, while we don't need to know in detail how to go from the name to the structure, a few hints can help us decode

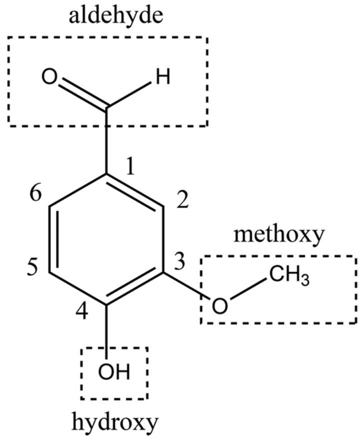


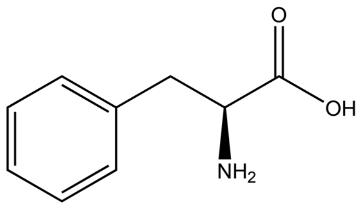
Figure 1.6 Structure of vanillin (4-hydroxy-3-methoxybenzaldehyde). The carbons in the hexagon are numbered 1–6, starting with the aldehyde (there are rules about where to start the numbering in those 133 pages of IUPAC instructions). The methoxy group is attached at position 3 and the hydroxy group (OH) at position 4.

the chemical names that I will use in this book. As a bonus, the chemical names that you see on many product labels will be less of a mystery.

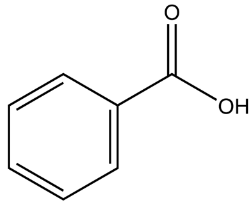
Consider the key compound responsible for the delicious scent of vanilla extract: 4-hydroxy-3-methoxybenzaldehyde (Figure 1.6). The "benz" in methoxybenzaldehyde tells a chemist that there is a flat hexagon of carbon atoms in the molecule, while hydroxy indicates the presence of an OH unit. Methoxy—a portmanteau of methyl and hydroxy—means there is also an OCH_3 unit. "Aldehyde" indicates the CHO cluster at the top of the molecule. Lots of aldehydes have pleasant aromas, so this is already a clue that 4-hydroxy-3-methoxybenzaldehyde might smell good. The numbers 3 and 4 tell a chemist where the methoxy and hydroxy units are attached to the hexagon.

Here are some general hints for decoding formal chemical names. Structures of the example molecules are shown in Figure 1.7.

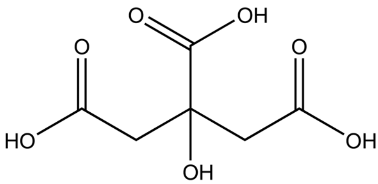
1. Words ending in -yl, -ane, -ene, or -yne indicate carbon chains. The length of the carbon chain is indicated by the stem of the word. Methyl, for example, is a carbon chain



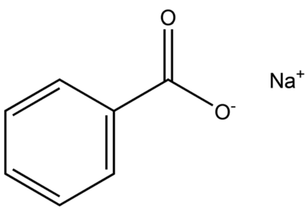
phenylalanine



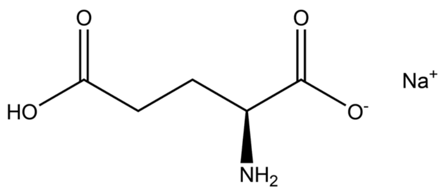
benzoic acid



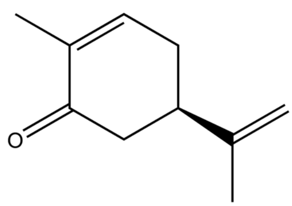
citric acid



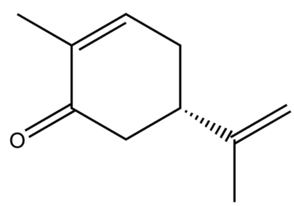
sodium benzoate



monosodium glutamate



spearmint
(R)



caraway
(S)

Figure 1.7 Molecular structures illustrating the connection between names and structures.

Table 1.1 List of commonly encountered stems for different lengths of carbon chains (and one uncommon stem).

No. of carbon atoms in chain	Stem	Etymology
1	Meth-	Derived from methanol, which was coined from the Greek for alcohol and wood; methanol is also known as wood alcohol and has only one carbon atom
2	Eth-	Takes its name from the anesthetic gas ether, which has two carbon atoms
3	Prop-	From propionic acid, a (foul-smelling) carboxylic acid with three carbon atoms, its name derived from the Greek for fat because it produces an oily layer in water
4	But-	From butter because the smell of rancid butter is caused by butyric acid, which has four carbon atoms
5	Pent-	From the Greek for five
6	Hex-	From the Greek for six
7	Hept-	From the Greek for seven
8	Oct-	From the Greek for eight
9	Non-	From the Latin (for a change) for nine
10	Dec-	From the Greek for 10
12	Dodec-	From the Greek for 12
31	Hentriacont-	Has nothing to do with chickens; from hen, the Greek for one, combined with triacont for 30, also from the Greek

with just one carbon atom, while pentene is a carbon chain with five carbon atoms. Cyclo- in front of a name indicates that the carbon chain is wrapped back onto itself. Table 1.1 lists some of the most common stems for different lengths of carbon chains, along with their etymology.

2. Numbers indicate the points of attachment of different molecular substructures—what chemists call functional groups.
3. "Phen" or "benz" mean there is a hexagonal planar substructure, as in phenylalanine or benzoic acid.
4. Hydroxy (–OH) groups are signaled by words ending in "-ol" (like alcohol, which is CH_3CH_2OH) or by the prefix hydroxy-. Sugar, as you might guess from the name, has lots of OH groups attached to it, eight to be exact. "-oxy" endings with a carbon chain prefix indicate an oxygen attached to a carbon framework, "ethoxy" means $-OCH_2CH_3$ is present.

5. "-oic" or "-ic" indicates an organic acid, meaning a COOH group is attached. Citric acid is an organic acid found in lemons and oranges.
6. "-ate" means there is an anion, a negatively charged ion, and, because opposites attract, there will be a positively charged counter ion—often sodium—present as well to balance it out. Sodium benzoate is a common preservative and monosodium glutamate (MSG) is used to enhance flavors.
7. For molecules that have mirror images, the letters *R* and *S* indicate which of the two reflections you have. *R* stands for *rectus* (Latin for right) and *S* for *sinister* (Latin for left). + and − or D (again from Latin, *dexter* for right) and L (*laevus* for left) are also used to indicate one of two mirror image molecules. For a longer explanation about mirror images, and their importance for biological molecules in particular, see the next section.

1.11 MOLECULES IN THE MIRROR

In 1848, the French chemist Louis Pasteur solved the mystery of why certain byproducts of wine-making spun polarized light in one direction, while molecules that appeared to have an identical formula and structure spun it in the other direction. When Pasteur examined crystals of the two compounds under a microscope, he noticed that their crystals were mirror images of each other—that is, one could not be superimposed on the other. The two molecules were therefore not identical, but were mirror images of each other. It rapidly became clear that living organisms were quite selective about which molecular mirror images they used and created.

Chemists call this property of having a non-superimposable mirror image chirality, from the Greek for hand. Hands are the archetypical chiral objects: your left hand is a mirror image of your right hand. The two hands cannot be superimposed on each other and, as a result, left gloves can only be put on left hands and right hands can only shake with right hands. Similarly, the handedness of a molecule can affect the handedness of things it can match up with.

Molecular chirality arises from the fact that carbon is tetrahedral. A tetrahedron has four vertices (Figure 1.8) and four faces.

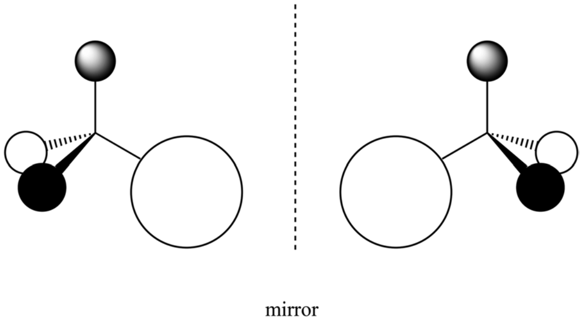


Figure 1.8 Tetrahedral carbon atom with four different groups attached and its non-superimposable mirror image.

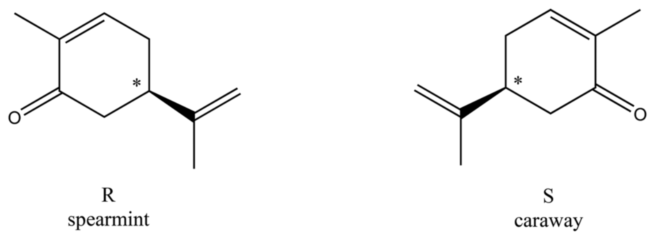


Figure 1.9 Structures of *R* and *S* carvone. The * indicates the chiral carbon atom, the atom that has four different groups attached to it, creating the potential for the two mirror images.

If you color each of the vertices a different color, you can create two different tetrahedrons that are mirror images of each other and cannot be superimposed. In the same way, a structure that contains a carbon atom with four different things attached to it, forming the vertices of a tetrahedron, will have a mirror image. Figure 1.9 shows the structures for caraway and spearmint oils with an asterisk indicating the carbon atoms that create the mirror image.

Chemists tag one image with the letter *R* and the other with the letter *S*. (There are a set of rules for determining which letter goes with which reflection.) Structures with multiple carbon atoms, each having four different things attached, have the potential for multiple mirror images. Each of these carbon centers is designated by either the letter *R* or the letter *S* depending on its configuration. Ordinary table sugar, for example, has nine of these centers! These are shown in Figure 1.10: four are *R* and five are *S*.

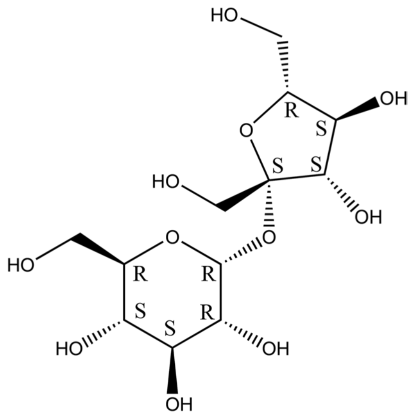


Figure 1.10 Structure of sucrose showing the nine carbon atoms that can have two mirror image configurations—chemists would call them stereogenic centers—each labeled with its absolute configuration, *R* or *S*.

Two older systems for labeling these molecular mirror images are still in use. Molecule names that include "+" in them rotate the plane of polarized light, as in Pasteur's experiments, in a clockwise direction. Molecules that rotate it in a counterclockwise direction have "−" in their names. (+)Carvone is an oil that smells of caraway seeds, while (−)carvone is an oil that smells like spearmint. The letters D and L are also seen in molecular names, such as in L-theanine, an amino acid that is found in tea. These also indicate mirror images. The designations refer to the similarity of each mirror image to the mirror images of glyceraldehyde, a common biological molecule. Unlike the *R* and *S* designations, which can tell you precisely the arrangement of the four groups around each carbon, or the + and − designations that tell you which way the compound will rotate polarized light, all D and L can tell you is that the compound is chiral and its handedness relative to the D and L forms of glyceraldehyde.[§§]

Biological systems are very discriminating when it comes to these mirror images. Of the more than 500 mirror combinations possible for sucrose, nature makes and recognizes only one.

[§§] *R*, *S* designations are referred to as absolute configurations because you can absolutely construct the arrangement of the four groups around the carbon based on the code. D, L designations are called relative configurations because they are determined relative to glyceraldehyde.

The structures of spearmint oil and caraway oil (Figure 1.9) are identical except that they are mirror images of each other. Despite their extraordinary similarity, your nose and taste buds would never confuse the two. Our DNA is right-handed, while proteins are built from the left-handed versions of amino acids. The sugars that our body metabolizes are all right-handed.

Makers of pharmaceuticals must be very careful about mirror images. The mirror images of some chiral drugs are less effective, or even ineffective, compared with their reflections. Others are toxic. The *S* mirror image of a common asthma drug, albuterol, does not work as a bronchodilator, but can cause hyperkalemia (an increase in the concentration of potassium ions that can disrupt heart action). Both the *R* and *S* versions of a common drug for combating acid reflux, omeprazole, are active, but the *S* version is more effective. It is marketed as a separate drug, esomeprazole for "es" + omeprazole.

1.12 POURING THE BIG IDEAS INTO A TEACUP

We now have a few key tools for unlocking the chemistry of tea. In the following chapters, we will see how we can use the four big ideas—atoms make up everything, structure dictates function, proximity, opposites attract—to understand what is happening in our cup of tea, starting from when the leaves are picked to when you take that first sip. Why is green tea green? How does a plant rearrange the carbon atoms it takes in from the air around us to make caffeine? Why does tea have that slightly astringent taste? Why should you skip the teabag? And just what is that white stuff on the top of the tea that you made using the microwave? With a little help from the four big ideas, all of these questions can be answered.

FURTHER READING

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L. Collingham, *The Taste of Empire: How Britain's Quest for Food Shaped the Modern World*, Basic Books, New York, NY, Illustrated edn, 2017. Chapters 6 and 11 take on the interplay between tea, Britain's colonization of India, and the opium trade.

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P. Ball, *Designing the Molecular World: Chemistry at the Frontier*, Princeton University Press, Princeton, N.J., 1st edn, 1994. A lively exploration of the relationship between molecular structure and function.

S. W. Smith, Chiral Toxicology: It's the Same Thing…Only Different, *Toxicol. Sci.*, 2009, **110**, 4–30. A slightly more technical discussion of chirality, with fascinating examples drawn from biochemistry and drug design.

A. Brunning, https://www.compoundchem.com/2015/08/27/org-comp-names/. A graphical guide to the names of molecules.

developed during the creation of a tea contribute to its physiological effects and to its taste and aroma. We will start with a look at caffeine: what it is doing in the leaf and what it does in our bodies. And we will unpack what happens with the polyphenols—the catechins—that are oxidized in black and oolong teas.

2.10 BREWING A BETTER CUP

If you are concerned about acrylamide, then choose a steamed green tea or a pu'erh tea.

FURTHER READING

K. Okakura, *The Book of Tea*, Officina Libraria, Rome, Italy, Annotated edn, 2022, A beautiful long-form essay written by a Japanese scholar visiting Boston in the early 20th century that situates tea within Zen Buddhism and Japan's cultural context.

M. Hartings, *Chemistry in Your Kitchen*, Royal Society of Chemistry, Cambridge, UK, 1st edn, 2016, A lucid explanation of the Maillard reaction and its importance in many aspects of kitchen chemistry, written for the non-chemist. There's also a section on that other beverage, coffee.

J. W. Uhl, *The Art and Craft of Tea: An Enthusiast's Guide to Selecting, Brewing, and Serving Exquisite Tea*, Quarry Books, Beverly, Massachusetts, Illustrated edn, 2015, A clear exposition of the process of making tea, from plucking the leaves to roasting them, with many beautiful color photographs.

P. Coucquyt, B. Lahousse and J. Langenbick, *The Art and Science of Foodpairing: 10,000 flavour matches that will transform the way you eat*, Firefly Books, Buffalo, N.Y, 1st edn, 2020, This exhaustive book on combining flavors includes a section on the basic structural motifs found in flavor molecules.

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and physical well-being in that cup as well. In the next chapter, we will explore some of the structures and functions of those molecules. Why is a cup of tea so calming, even given the caffeine it contains? What makes tea an antioxidant? Are there health risks as well as health benefits to drinking tea?

3.14 BREWING A BETTER CUP

- To decaffeinate tea at home, take a teabag (or a teaspoon of loose tea) and add about a quarter cup of boiling water. Let the teabag steep in the water for 30 seconds (three minutes for the loose tea). Discard the water and re-brew the tea leaves for five minutes in a fresh cup of boiling water. This will remove more than 80% of the caffeine.
- Letting tea steep longer than recommended will not give you an extra-caffeinated cup of tea, just an increasingly bitter-tasting brew.
- The hotter the water, the more caffeine will be extracted; for maximum caffeine, use boiling water.
- Never reuse a teabag if you want any caffeine in your second cup; virtually all of the caffeine has been extracted after steeping for less than a minute.

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but has made me a better cook as well. This is a readable and intriguing book about food and smell.

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- If you are reheating your tea in the microwave, add a bit of lemon to dissolve the tea scum and reduce creaming.
- Compost your tea leaves if you can—it reduces global warming by a tiny fraction. It doesn't improve your cup, but it makes for a better world.

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H. Chang, *Inventing Temperature: Measurement and Scientific Progress*, Oxford University Press, Oxford, New York, Illustrated edn, 2007. A fascinating tour of the history of temperature and its measurement. We take thermometers for granted, but their development was not straightforward.

G. Orwell, *A Nice Cup of Tea*, https://www.orwellfoundation.com/the-orwell-foundation/orwell/essays-and-other-works/a-nice-cup-of-tea/. From the author of *1984*, advice on making the best cup of tea, much of which is supported by the science in this chapter.

Lu Yu, *Classic of Tea*. The edition in ref. 3 is beautifully illustrated and includes a substantial amount of historical context.

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tea in, the type of teapot or teacup, can improve the experience as much as what we add to the tea itself. In the last chapter of this book, we explore the equipment we use to make tea and the materials that make for the best cup and pot.

6.13 BREWING A BETTER CUP

- If you like milk in your tea, add it first for the very best cup. If you must add the milk after the tea, you would do well to gently warm the milk first.
- If tea is too bitter for your taste, a sweetener can moderate the bitterness or you could add a pinch of salt.
- Having a bad day? Consider making a cup of jasmine or Earl Grey tea and inhaling the aromatic steam.

FURTHER READING

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Chemists still use the glass-walled version of a thermos, as do tea enthusiasts. Chemists call it a dewar (for James Dewar, the Scottish chemist who invented the contraption in 1892). The double-walled teapot that so ably kept the temperature of the water high is a glass dewar, wrapping the tea in a vacuum, a sort of nothingness. Vacuum doesn't quite mean a complete absence of molecules—practically, it means a very low pressure gas. Even interstellar space has roughly 10 atoms per cubic meter. A chemical dewar has a pressure of about 0.01% of the air pressure at sea level, containing on the order of a billion trillion (10^{21}) atoms per cubic meter.

Exploring the thermal properties of my teacups and teapots has given me a new set of favorites, cups and pots that inarguably give me a better cup of tea. I cleaned out my collection of tea infusers and kept only the largest of my tea baskets. And while I appreciate the convenience of a teabag, I am more convinced than ever that my tea caddies filled with whole tea leaves are the gateway to a superb cup of tea. More than 50 years after my mother held out that steaming, sweet mug of Lipton tea, I am still learning to brew a better cup. I hope that you, too, have found a few ways to improve your cup, whether made from a teabag, or whole leaves, or reheated in the microwave.

7.6 BREWING A BETTER CUP

- Don't let anything come between you and your tea. Use loose-leaf tea or a large brewing basket, preferably made from stainless steel.
- Warm the teacup or teapot before steeping.
- Don't use teabags made from plastic, natural or not, if you are concerned about microplastics. Choose paper.
- Cover your teapot or teacup to keep it warm.
- Be nice to the planet and don't heat more water than you need for a cup or pot. Compost your tea leaves and teabags.

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